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Evaluation of Lenses for Use in All-Sky Photometers

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Evaluation of Lenses for Use in All-Sky Photometers*

by

Guy E. Barasch

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ABSTRACT

For maximum performance, an all-sky photometer should have a large light-collection area and a narrow spectral passband; however, for a given size of photometer, these parameters cannot be optimized simultaneously. Three compromise lens designs are evaluated here: LASL-2, a 0.43-in.-focal length, f/2.8, 160°-field-of-view lens for use with a 2-in.-diam. photomultiplier tube; and, for use with 5-in.-diam. photomultiplier tubes, LASL-5, a 2.1-in.-focal-length, f/4.0, 120°-field-of-view lens; and EG&G-5, a lens with a nominal 120° field of view, which can be used with or without an ND2 filter covering the central part of the first element. The effective on-axis entrance-pupil areas and the relative response curves as a function of wavelength and incidence angle were measured, and the results are reported.

The maximum effective entrance pupil areas for a monochromatic source at 3914 Å, for LASL-2, LASL-5, EG&G-5 with ND2, and EG&G-5 without ND2, are 0.014, 0.23, 0.36, and 2.6 cm^2, respectively, when interference filters of 20-Å half-width and 35% maximum transmittance are used. With the exception of LASL-5, the effective bandwidths depend on incidence angle; the ranges of variation within the nominal fields of view of the four 3914 Å photometers are 39 to 49 Å, 25 Å, 33 to 80 Å, and 26 to 75 Å, respectively. Peak-response wavelengths decrease with increasing incidence angle; overall shifts are 6 Å, 6 Å, 45 Å, and 40 Å, respectively. LASL-2 and LASL-5 have also been evaluated at 6563 Å; performance of the former is badly degraded, while that of the latter is unchanged relative to 3914 Å. Therefore, LASL-5 photometers are recommended for systems like the Los Alamos Air Fluorescence Detection System, which for optimum performance require wide-field photometers with narrow, well defined, spectral passbands.

I. INTRODUCTION

The Los Alamos Air Fluorescence Detection System (LAAFDS)[1] uses a ground-based all-sky photometer system to measure the pulse of N_2^+ 1N (0,0) (3914 Å) fluorescence excited in the upper atmosphere by thermal x rays incident from a nuclear explosion in space. A second photometer ("discrimination detector") is used to measure the source spectrum simultaneously at a wavelength other than 3914 Å. The

two measurements theoretically determine unambiguously the type of spectrum detected and are used to ascertain the type of source which produced it.

To maximize the distance beyond the atmosphere at which the standard 1-kt x-ray source can be detected, the photometers must have large light-collection areas, i.e., entrance pupils. They must also have narrow spectral passbands, for two reasons: to limit the noise signals produced by fluctuations in the detection of background light during daylight operation, and to obtain the spectrum recognition required to discriminate false signals such as those produced by lightning. In practice, given size or cost limitations, a wide-angle lens for use in an all-sky photometer cannot be designed to maximize the entrance-pupil area and to minimize the spectral bandwidth simultaneously. A compromise design must be used which, for example, maximizes the entrance-pupil area while widening the spectral passband as little as possible. Another possible solution is to maximize the entrance pupil and then determine how broader-than-optimum spectral passbands can be employed.

Three designs of all-sky lenses are evaluated in this report. One is the original LASL lens* designed for the LAAFDS; two are second-generation designs**,†,[2] which have been proposed for use in extended-range detection systems, or for discrimination purposes, or both. Their effective entrance-pupil areas, for on-axis rays, and spectral passband curves for on- and off-axis rays are reported.

A value purported to be the effective entrance-pupil area of the original LASL-designed all-sky lens has been used to derive the effective collection area at 3914 Å for a LAAFDS evaluation.[3] The origin of the value is unknown. For the same lens, Tomlinson[4] predicted theoretical relative spectral-passband curves for light near 3914 Å; he did not attempt to carry the calculations to other spectral regions.

The measurements reported here were prompted by the need for accurate knowledge of the spectral-passband characteristics of the lenses required for:

1. Analysis of the 1965 lightning study data.[5,6]
2. Improvements to the LAAFDS.
3. Discrimination requirements of advanced systems.

We also wished to check the accuracy of Tomlinson's predictions.

This evaluation comprises measurements of the dependence of the response of all-sky photometers on parameters of the lenses used in them. The term "response" is used to mean "output," whatever the units. Care was exercised to minimize the dependence of the results on the associated photometer components. The data required for the evaluation are presented in three parts: the criteria by which photometer performance is related to lens parameters (Section II); descriptions of the lenses (Section III); and the measurement techniques and results (Section IV).

II. PHOTOMETER-PERFORMANCE CRITERIA

There are two considerations by which photometers designed for use in the LAAFDS or similar systems can be evaluated. First, the signal-to-noise ratio should be as large as possible. The parameters which affect signal-to-noise ratio depend on the type of spectrum to be detected and on the optical environment, and include entrance-pupil area, field of view, and details of the spectral passband. Second, the responses to sources with different spectra, i.e., air fluorescence vs lightning, must be sufficiently and consistently different so that the source spectra can be recognized and the sources differentiated on the basis of the photometer response. Relevant photometer characteristics are details of the spectral passband: its width, shift, and uniformity of shape as a function of incidence angle.

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*LASL type 10, a glass, 0.43-in., f/2.8 lens designed by B. Brixner of LASL in 1960, using an early lens-design code. See Fig. 1. Designated LASL-2 in this report.

**LASL type 67, a quartz, 2.1-in., f/4.0 lens designed by Brixner in 1965. See Fig. 2. The design technique[2] for this lens is an outgrowth of the earlier code. Designated LASL-5.

†An EG&G, Inc.-designed lens shown on EG&G drawing No. 106998 (Jan. 1966). See Fig. 3. Designated EG&G-5. This lens is not the scaled-up version of the first LASL design.

A. Signal-to-Noise Ratio

The derivation of signal-to-noise ratio in the output of a photometer in terms of input signals and photometer parameters is straightforward, and can be accomplished with as much detail as desired. One presentation which treats of the signal-to-noise level of the IAAFDS specifically has been given by Donahue.[7] The treatment in this section is limited to a calculation of the dependence of signal-to-noise ratio on overall photometer parameters, such as field of view.

1. Noise Level. For daylight operation, the photometers used in the IAAFDS are shot-noise limited, internal noise sources being small compared to statistical fluctuations in the background light detected. The noise level is proportional to the square root of flux, F_b, which can be written

$$F_b = B_\lambda \Omega_e A_e \Lambda_e \text{ watt,}$$

where

B_λ = average background spectral radiance ($W\ cm^{-2}\ Å^{-1}\ sr^{-1}$),

Ω_e = effective solid angle of photometer (sr),

A_e = effective entrance-pupil area (cm^2),

and

Λ_e = effective spectral bandwidth (Å).

For night operation, the photometers produce an internal noise level which depends on the size of the photomultiplier tube required but which otherwise is independent of lens characteristics.

In a rigorous analysis the noise level cannot be defined until a frequency interval, f(Hz), in which the noise is measured has been defined. In the IAAFDS the frequency interval is the electrical bandwidth of the triggering circuits. This report, however, does not treat of the dependence of signal-to-noise ratio on frequency interval.

2. Signal Level. The signal in a photometer is proportional to the flux, which can be written for two significant cases. The immediate source is assumed to be localized in the detector's field of view, at an angle θ from the (vertical) photometer axis. Because the source is localized, its important characteristic is the irradiance, H ($W\ cm^{-2}$), at the detector.

First, if the spectrum of the source is mono chromatic at wavelength λ_o within the spectral passband, the flux is

$$F_m = H_o A_e R(\lambda_o, \theta) \text{ watt,}$$

where

H_o = source irradiance at wavelength λ_o ($W\ cm^{-2}$),

and

$R(\lambda_o,\theta)$ = response of photometer at λ_o and angle θ, relative to θ = 0.

Second, if the spectrum is a smooth continuum, with average spectral irradiance H_λ ($W\ cm^{-2}\ Å^{-1}$), the flux is

$$F_c = H_\lambda A_e R_{max}(\theta)\ \Lambda(\theta) \text{ watt,}$$

where $[R_{max}(\theta)\ \Lambda(\theta)]$ is the wavelength integral (Å) of the relative-response curve at incidence angle θ. [$\Lambda(\theta)$ is the effective spectral bandwidth (Å) at angle θ.]

3. Signal-to-Noise Ratio. The dependence of signal-to-noise ratio on photometer parameters has been isolated and is given in Table I for two backgrounds and two types of source spectrum.

Table I. Dependence of Signal-to-Noise Ratio on Photometer Parameters

Spectrum	Daylight	Night
Monochromatic	$R(\lambda_o,\theta)\left[\frac{A_e}{\Omega_e\Lambda_e}\right]^{1/2}$	$R(\lambda_o,\theta)A_e$
Continuous	$R_{max}(\theta)\Lambda(\theta)\left[\frac{A_e}{\Omega_e\Lambda_e}\right]^{1/2}$	$R_{max}(\theta)\Lambda(\theta)A_e$

Two general conclusions can be drawn from the data in Table I. The signal-to-noise ratio:

a. increases with increasing effective entrance-pupil area, A_e, as $\sqrt{A_e}$ during daylight and linearly at night; and

b. increases with decreasing spectral bandwidth

for a monochromatic source spectrum during daylight, but increases with increasing spectral bandwidth for continuum sources, day or night.

Thus, maximum performance calls for large entrance pupils regardless of source or environment, a narrow spectral passband when the source spectrum is monochromatic, and a spectral passband as wide as is practical when the source is a continuum. In the latter case the upper limit on the spectral bandwidth is determined by the requirement for spectrum recognition.

B. Spectrum Recognition

The system for lightning discrimination on the basis of spectral differences operates as follows. When a signal with a short rise time is detected by the IAAFDS detector at 3914 Å, the response maximum is compared with the corresponding maximum of the discrimination-detector response. The ratio of the two signals is used to decide, on the basis of possible variations of the expected source spectra, which type of source produced the pulse.

The maximum reliability of discrimination is attained when the difference between the responses to the two types of sources is maximum. Thus one tries to find two spectral regions, (a) where one source is relatively weak and the other strong, and (b) vice versa. The weak and strong regions depend in degree upon the spectral bandwidth over which the spectra are averaged: narrow bandwidths can be fit to maxima and minima in the spectra much more readily than broader ones. Hence, one of the requirements for adequate spectrum recognition is a sufficiently narrow spectral passband.

The 3914-Å N_2^+ 1N band used for air fluorescence detection contains a large fraction of its energy in a spectral region a few angstroms wide. Since the lightning spectrum is mainly continuum near 3914 Å,[6] the greatest photometer-response difference between the two spectra at 3914 Å can be attained by employing as narrow a spectral passband as possible.

The optimum width of the discrimination-channel spectral passband depends on the spectral region chosen for discrimination, and whether a line feature or an apparent continuum is to be detected in lightning. It has already been noted that when detecting a line feature, the bandwidth should be minimized. However, for detection of a continuum, the channel should be as broad as possible while still maintaining an adequate response difference. Optimum widths, estimated from the typical lightning spectrum[6] and the Starfish high-altitude air-fluorescence spectrum,[8] for a number of possible discrimination channels, are given in Table II.

Table II. Estimated Optimum Bandwidths for Discrimination Channels

Nominal channel wavelength, Å	4140	4900	5000	6563
Lightning feature (C = continuum)	C	C	NII	Hα
Clear region, Starfish, Å	4080-4160	4730-4990	some NII	6545-6570
Estimated optimum bandwidth, Å	40	130	< 20	< 20
Optimum center wavelength, Å	4120	4860	5000	6563

It is also essential for proper operation of the discrimination system that the photometer response be an unambiguous function of the source spectral characteristics, regardless of where in the field of view the light originates. Possible causes of response ambiguity are as follows.

1. Ambiguity of response occurs if the spectral bandwidth becomes larger than its optimum, or changes considerably, anywhere within the field of view. Either action decreases the response difference, owing to extraneous contributions to the response from parts of the spectrum outside the desired passband or to uncertainties in the stimulus-to-response transfer function.

2. A shift of the peak-response wavelength can completely change the emphasis of adjacent spectral features and cause gross changes in the desired response difference. For example, a relatively small wavelength shift in the 3914-Å channel peak wavelength can, if the bandwidth is narrow, partially negate the contribution of the N_2^+ 1N (0,0) 3914-Å feature for off-axis rays. In the worst case, this ambiguity could cause an air fluorescence signal produced by a nuclear explosion in space to be rejected by the discrimination system.

There is, of course, some acceptable relaxation from the optimum parameters for a given discrimination channel, as will be discussed in Section V.

III. LENS DESCRIPTIONS

The three wide-angle lens designs for use in all-sky photometers are described in Figs. 1 to 3 and in Table III. The LASL-2 was designed by B. Brixner for use in the original LAAFDS. The LASL-5 is a new design by Brixner, intended for use in an extended-range LAAFDS, in both the detection and discrimination channels. The EG&G-5 design is intended for use in an advanced system in which photometers are required for lightning-discrimination purposes only.

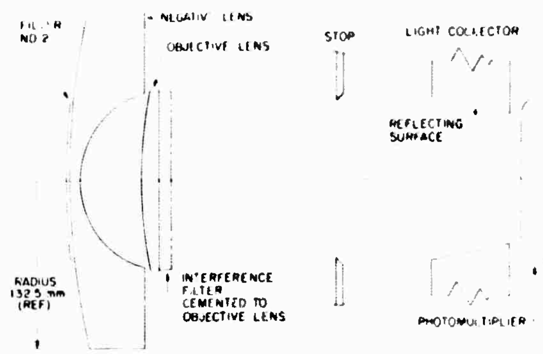
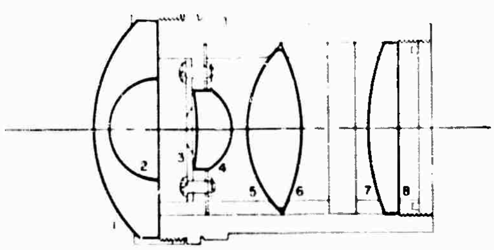


Fig. 3. EG&G-5 all-sky lens.

Table III. All-Sky Photometer Lenses[a]

	LASL-2	LASL-5	EG&G-5
Date designed	1960	1965	1965
Nominal field	160°	120°	120°
Focal length	0.43 in.	2.1 in.	-
Aperture	f/2.8	f/4.0	-
For photomultiplier	2 in.	5 in.	5 in.
No. of elements	4	5	2
Filter diameter	1.5 in.	4 in.	5.5 in.
Lens diameter	2 in.	6 in.	11 in.
Lens length	3 in.	41 in.	15 in.
Optics material	glass	quartz	glass

[a]See footnotes on p. 4



SURFACE	RADIUS POSITIVE FOR CONVEX RADIUS NEGATIVE FOR CONCAVE	AXIAL THICKNESS	TRIM DIAMETER
1 2	1.300 ± .010 -0.476 ± .005	0.150 ± .010	1.875 +.000 -.002
3 4	+2.000 ± .015 0.409 ± .005	0.30[illegible] ± .015	0.3437 +.000 -.002
5 6	1.000 ± .010 1.544 ± .010	0.500 ± .015	1.400 +.000 -.002
7 8	1.924 ± .010 ∞	0.300 ± .015	1.400 +.000 -.002
LENS MATERIAL - CROWN GLASS, BOROSILICATE, N 1.530			

Fig. 1. LASL-2 all-sky lens.

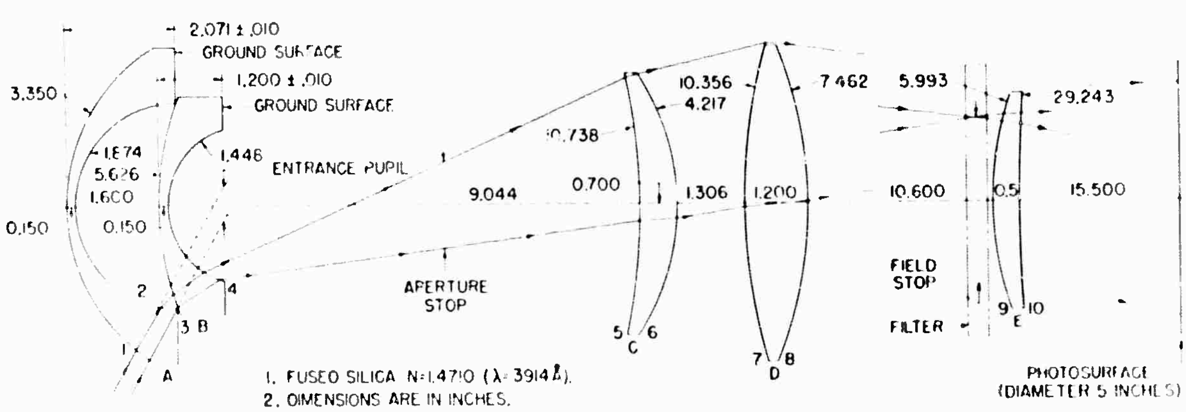


Fig. 2. LASL-5 all-sky lens.

IV. MEASUREMENTS AND RESULTS

The comparative evaluation of the performance of the three lenses to be given in Section V uses as a basis the results of two series of measurements, (a) effective entrance-pupil areas for an on-axis parallel beam of light, and (b) spectral-passband curves. The latter give four results as functions of incidence angle: relative response vs wavelength; relative response for monochromatic and continuum sources; shift of the peak wavelength of the spectral passband; and effective width of the spectral passband ("bandwidth"). Details of the measurement techniques and results are given below.

The measurements were made at three wavelengths for the IASL-2, at two for the IASL-5, and only at 3914 Å for the EG&G-5. This disparity has two sources. In the case of the IASL-5, no interference filter of the proper diameter was available near 5577 Å. For the EG&G-5, the interference filter near 3914 Å was cemented to one of the lens elements and thus could not be replaced for measurements at another wavelength region.

A. Entrance-Pupil Area

The effective entrance-pupil area, defined as the product of the geometrical entrance-pupil area and the transmittance of the optics, was measured for each lens at a number of wavelengths, using the apparatus outlined in Fig. 4. A stable tungsten source was used with a baffle system to produce a beam with a divergence half-angle less than 2°.

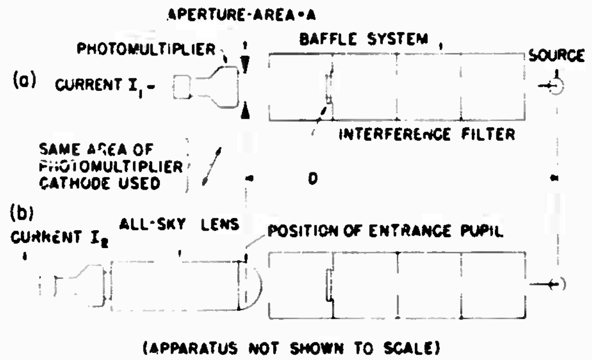


Fig. 4. Apparatus for measurement of effective entrance-pupil area A_e. (a) Response current I_1 for known area A. (b) Response current I_2 for entrance pupil A_e. Result: $A_e = A(I_2/I_1)$.

The entrance pupils of the IASL-designed lenses were measured with the interference filters removed from within the lens assembly; interference filters were placed in the beam outside the lens, as shown, to define the limited spectral regions at which the measurements were made. Light that passed through an aperture of known area, A, at a given distance from the source [Fig. 4(a)] was compared with light that passed through the entrance pupil of the lens, at the same distance from the source, and was transmitted by the optics [Fig. 4(b)]. The light source and photomultiplier were identical for the two measurements. The light signals were in the same ratio as the effective areas, i.e. $A_e/A = I_2/I_1$.

Because the interference filter for the EG&G-5 lens could not be removed, the measurement of its entrance pupil was not straightforward and is less accurate. The experiment shown in Fig. 4(a) was performed with a standard lamp as the source, and with an interference filter of known spectral transmittance, in order to calibrate the photomultiplier. The interference filter in the incident beam was then removed, and the same source and the calibrated photomultiplier were used to measure the product of the filter's spectral-passband transmittance and the effective entrance pupil of the lens. The transmittance of the internal filter as provided by EG&G[9] was used as a correction to give a value of what the effective entrance-pupil area would be without the filter.

The effective entrance pupil areas determined are given in Table IV.

Table IV. Effective Entrance-Pupil Areas

Lens	Geometrical Entrance Pupil Area (cm^2)	Wavelength (Å)	Effective Entrance Pupil Area (cm^2)
IASL-2	0.12	3914	0.079
		6563	0.094
IASL-5	1.4	3914	0.85
		6563	0.92
EG&G-5	14.5[a]	3914	9.5 ± 3

[a]See Reference 10.

B. Spectral Passband Characteristics

The response of each lens-filter-photometer combination to a uniform monochromatic parallel beam of light which filled the entrance pupil was measured as a function of wavelength and incidence angle using the apparatus shown in Fig. 5. A uniformly filled f/10 cone of monochromatic light was formed by a Jarrell-Ash Model 82-000, 0.5-m, grating, scanning, "Ebert" monochromator. The light source was a ribbon-filament 100-W tungsten projection lamp. A parallel beam was formed by placing an achromatic lens at its focal distance from the exit slit; angular divergence of the beam was less than 1° full angle. The all-sky photometer was mounted on a large tripod with gear-driven angular positioning; angles could be set to ± 2°. The photometer was positioned so that the parallel beam covered the entrance pupil for all incidence angles used; the beam was always appreciably larger in diameter than the entrance pupil.

The measurements were made by the following procedure. The photometer was mounted on the tripod and rotated to 0° incidence angle. The monochromator slits were set to give a usable signal, but never so large that the spectral width of its beam at half-maximum was > 6 Å. The electric grating drive of the monochromator was scanned through the spectral passband of the photometer; the response current was recorded on synchronously-moving chart paper. Wavelength-calibration marks were applied to the chart paper at the beginning and end of the scan. This procedure was repeated at all incidence angles. Variations of relative irradiance of the monochromatic beam were recorded by replacing the photometer with a previously-calibrated photomultiplier tube* and recording its output during a scan over the same wavelength region.

The chart data were read, typically every 4 Å, and punched on cards. Reduction of the data, including corrections for source wavelength variation, was carried out by computer. The results for each photometer were plots of response, relative to the maximum response recorded, vs wavelength, one plot for each value of incidence angle. These plots of relative response as a function of wavelength and incidence angle are given in Figs. 6 - 12. Each wavelength scale was shifted as necessary to produce maximum response at 3914, 5577, or 6563 Å.

*Provided by W. Gould.

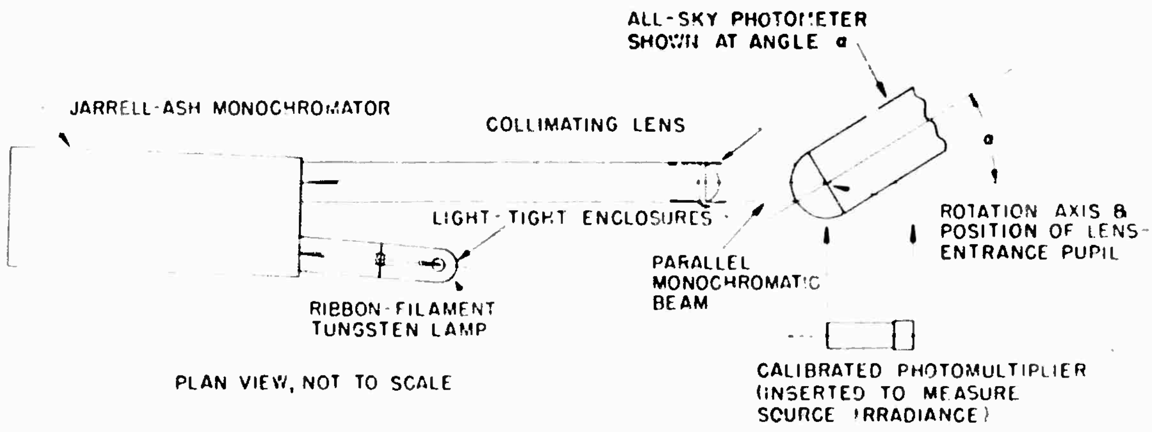


Fig. 5. Apparatus for measurement of spectral-passband curves. Measurement shown for incidence angle α. Light from tungsten lamp passed through monochromator and collimating lens, forming large parallel monochromatic beam. Monochromator was scanned in wavelength; photometer output current was recorded on chart paper. Calibrated photomultiplier was used to record source variations.

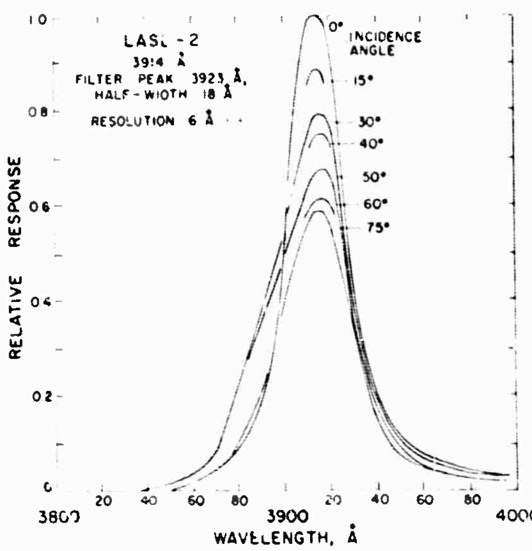


Fig. 6. Relative response of 3914 Å LASL-2 photometer vs wavelength and incidence angle.

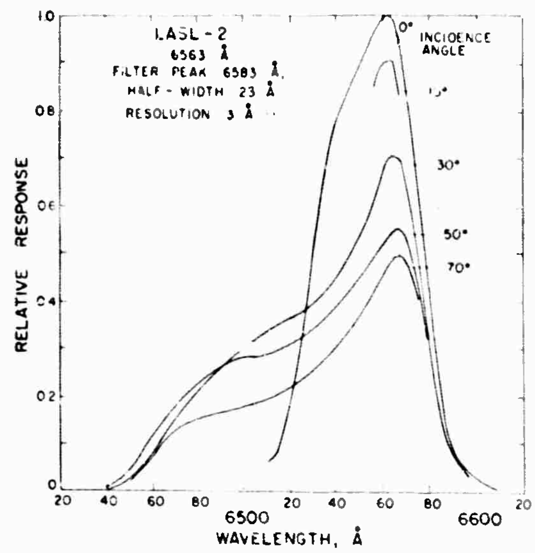


Fig. 8. Relative response of 6563 Å LASL-2 photometer vs wavelength and incidence angle.

A number of parameters by which the photometers can be evaluated were obtained from the curves of relative response vs wavelength and incidence angle. Figure 13 shows plots of relative response vs incidence angle of each of the photometers to sources with spectra of two types: one, a uniform continuum; the other, monochromatic at the design wavelength of the photometer. Values for the plots of continuum-source response were obtained by integrating the spectral response curves over wavelength.

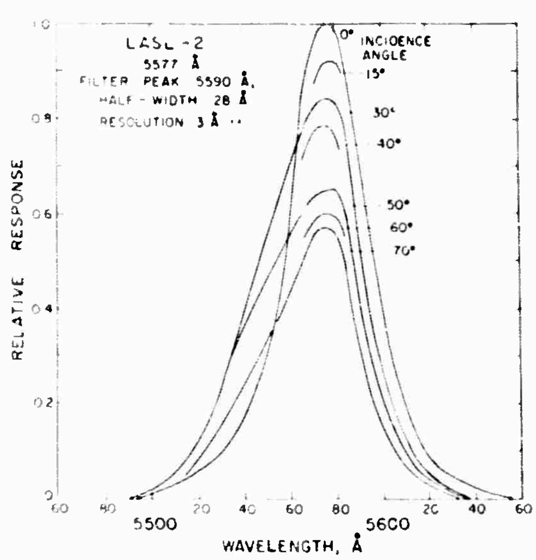


Fig. 7. Relative response of 5577 Å LASL-2 photometer vs wavelength and incidence angle.

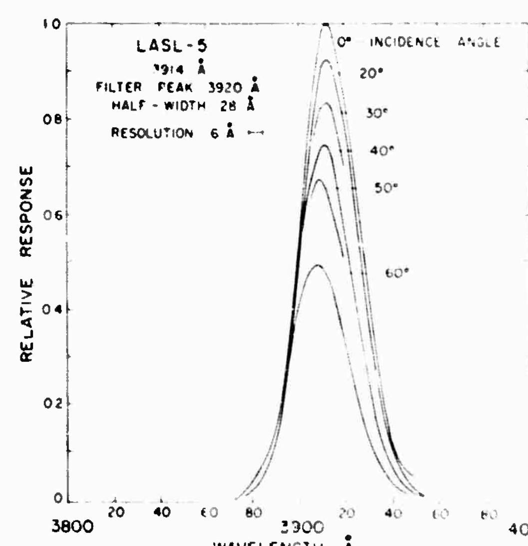


Fig. 9. Relative response of 3914 Å LASL-5 photometer vs wavelength and incidence angle.

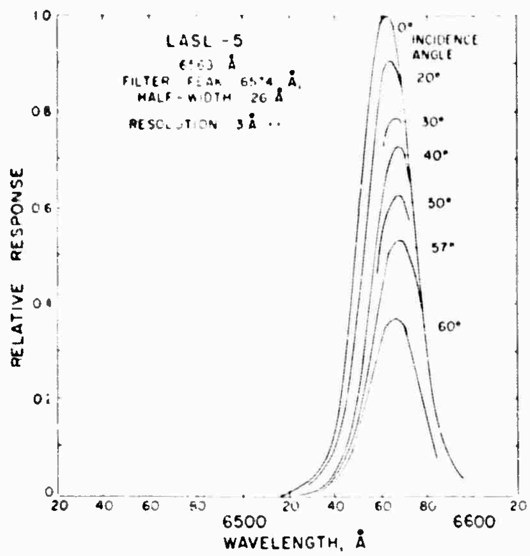


Fig. 10. Relative response of 6563 Å LASL-5 photometer vs wavelength and incidence angle.

Values for the monochromatic-source response were obtained by reading points off the curves, e.g., at 3914 Å.

Figure 14 shows the shift of the peak-response

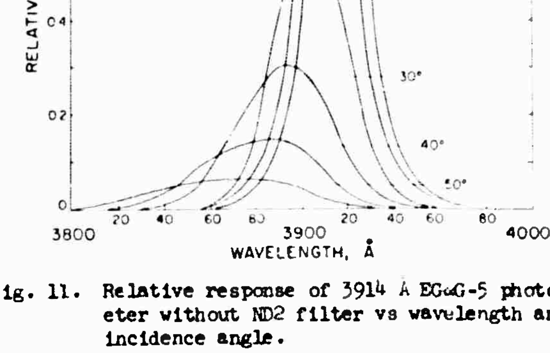


Fig. 11. Relative response of 3914 Å EG&G-5 photometer without ND2 filter vs wavelength and incidence angle.

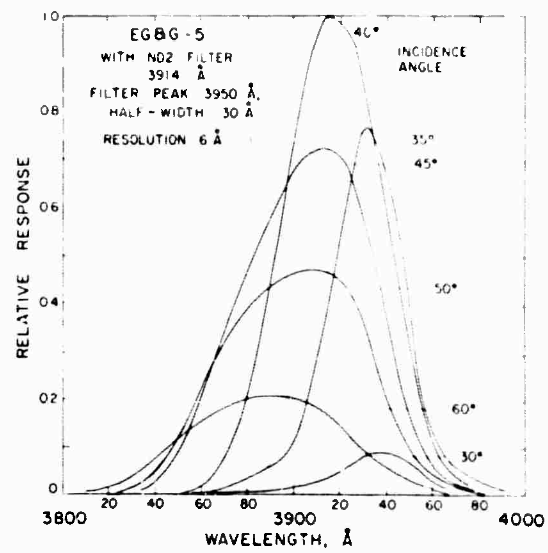
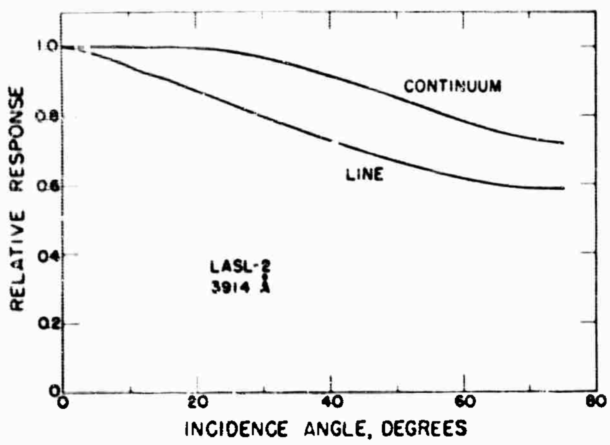


Fig. 12. Relative response of 3914 Å EG&G-5 photometer with ND2 filter vs wavelength and incidence angle.

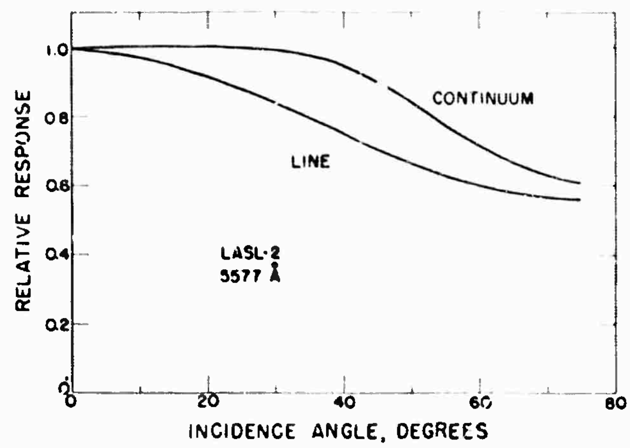
wavelength, with changes in incidence angle, of each of the photometers, relative to the peak-transmittance wavelength of the interference filter.

Finally, it is desirable for intercomparison of the lenses to have curves of effective spectral bandwidth, defined as the wavelength integral of the response curve divided by its maximum [$\Lambda(\theta)$ of Section II], vs incidence angle. However, for meaningful comparisons, the spectral bandwidths of the interference filters used in the lenses should be equal, or correction should be made for different-bandwidth filters. Figure 15 shows plots of the spectral bandwidths for each of the photometers, as predicted for 20 Å-wide interference filters, vs incidence angle. Corrections for filter widths, W_F, different from 20 Å were made by the expression $W_C = [W_M^2 + (20\ \text{Å})^2 - W_F^2]^{1/2}$, where W_M is the measured effective width and W_C is the corrected width.*

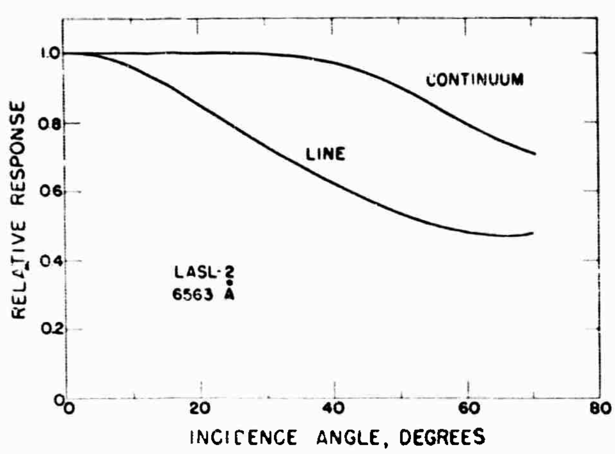
*This correction is exact if the spectral passbands are Gaussian in shape, and is a good approximation if either $W_M >> W_F$ or the shape is approximately Gaussian.



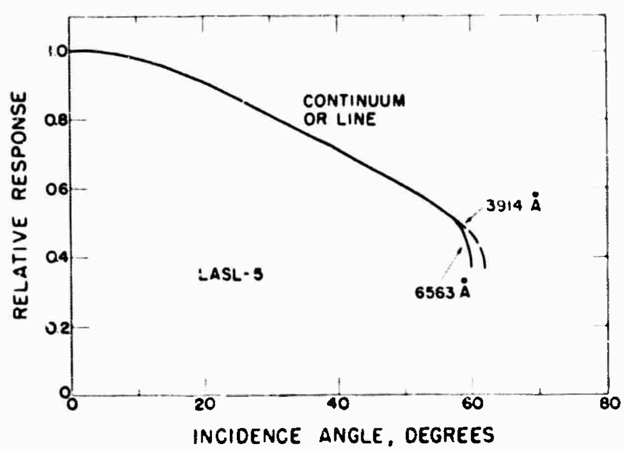
(a) 3914 Å LASL-2



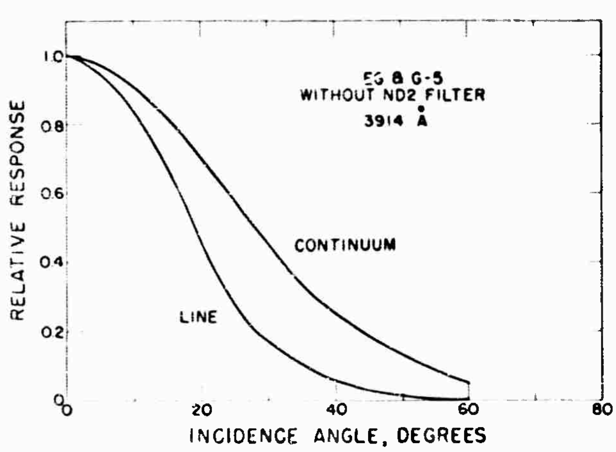
(b) 5577 Å LASL-2



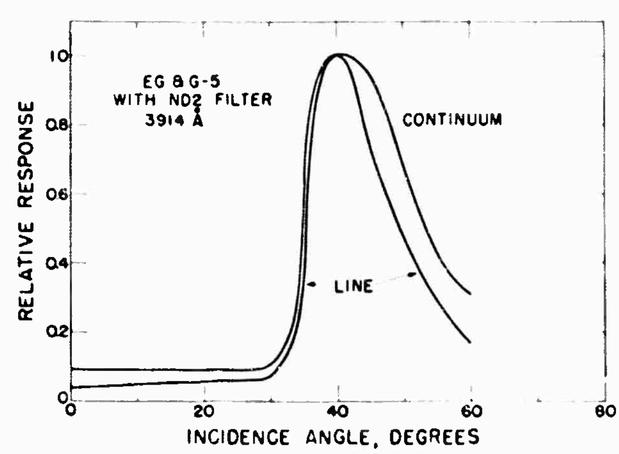
(c) 6563 Å LASL-2



(d) 3914 Å and 6563 Å LASL-5

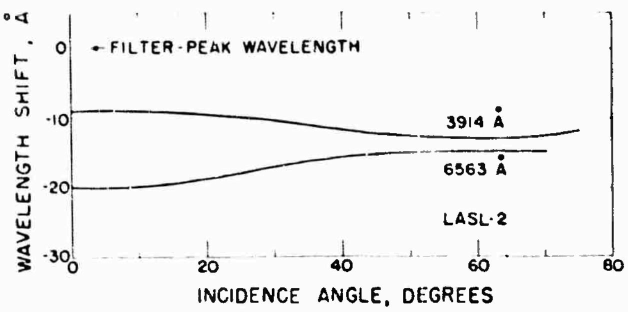


(e) 3914 Å EG&G-5, without ND2 filter

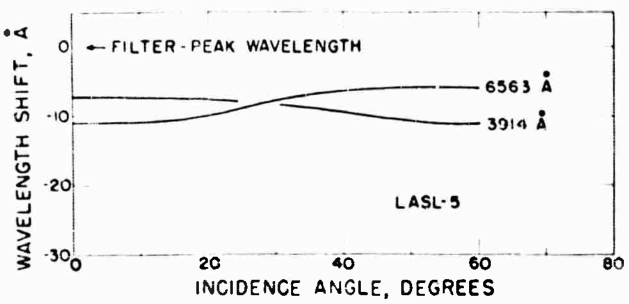


(f) 3914 Å EG&G-5, with ND2 filter

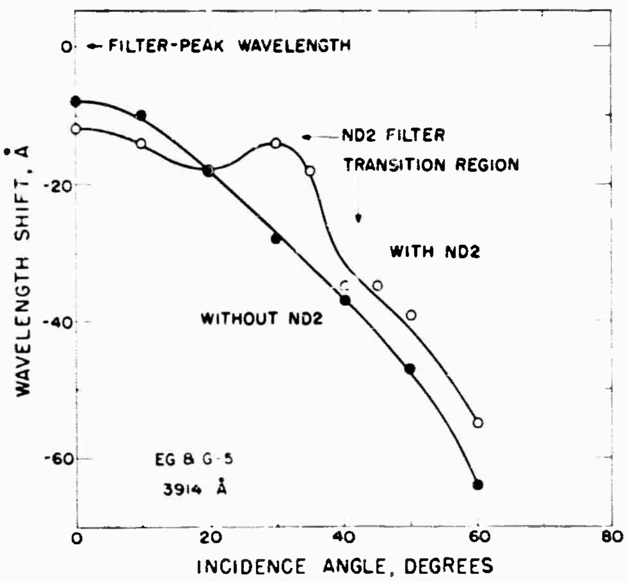
Fig. 15. Relative photometer responses to line- and continuous-spectrum sources vs incidence angle. Line spectrum is monochromatic at design wavelength; continuous spectrum is uniform. Curves are normalized separately.



(a) LASL-2

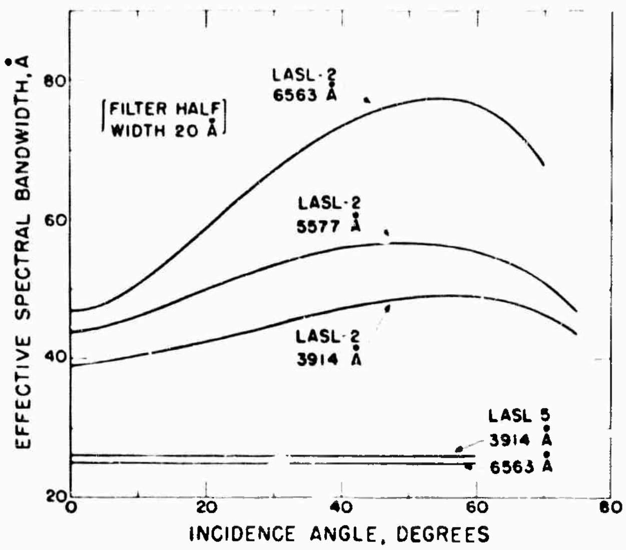


(b) LASL-5

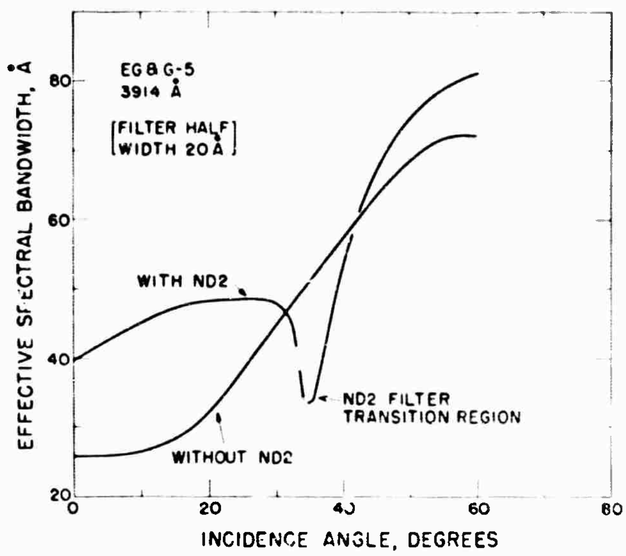


(c) EG&G-5

Fig. 14. Shift of peak-response wavelength, relative to filter-peak wavelength, vs incidence angle.



(a) LASL-2 and LASL-5

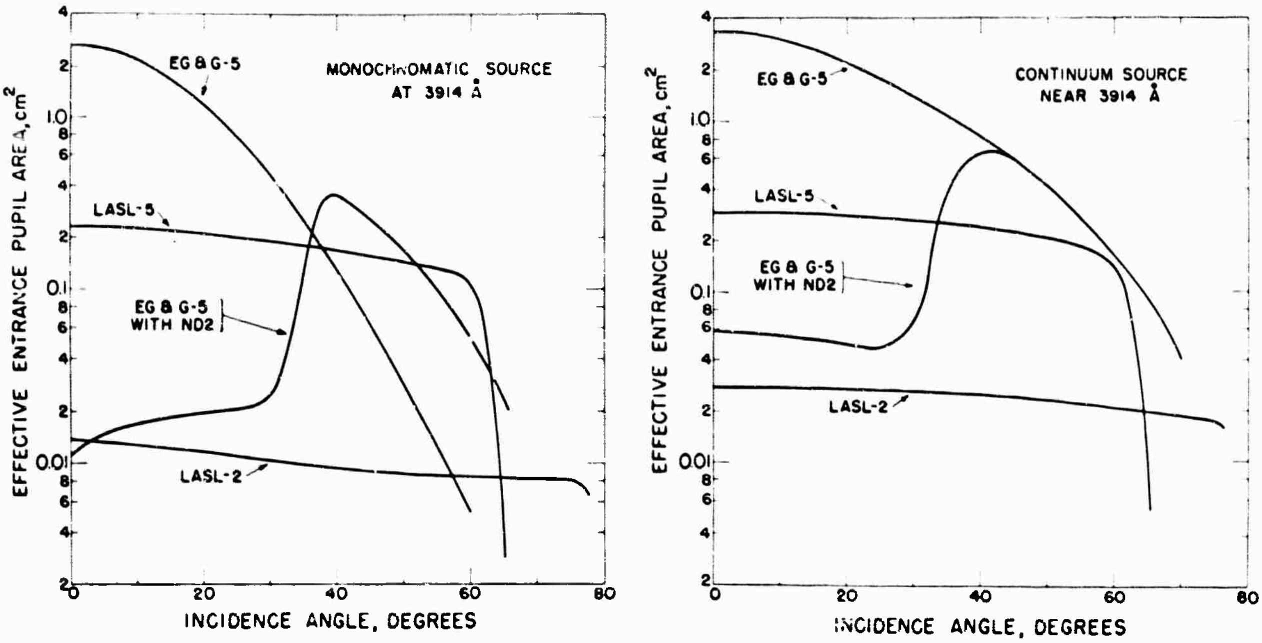


(b) EG&G-5

Fig. 15. Spectral bandwidth using 20-Å-half-width filter, vs incidence angle. See text for discussion of derivation of these data.

V. COMPARISONS, EVALUATIONS, AND RECOMMENDATIONS

In this section, the continuum- and line-source response curves of the lenses are given on an absolute scale, so that comparisons can be made. The passband shift and broadening data are evaluated in terms of the criteria presented in Section II.



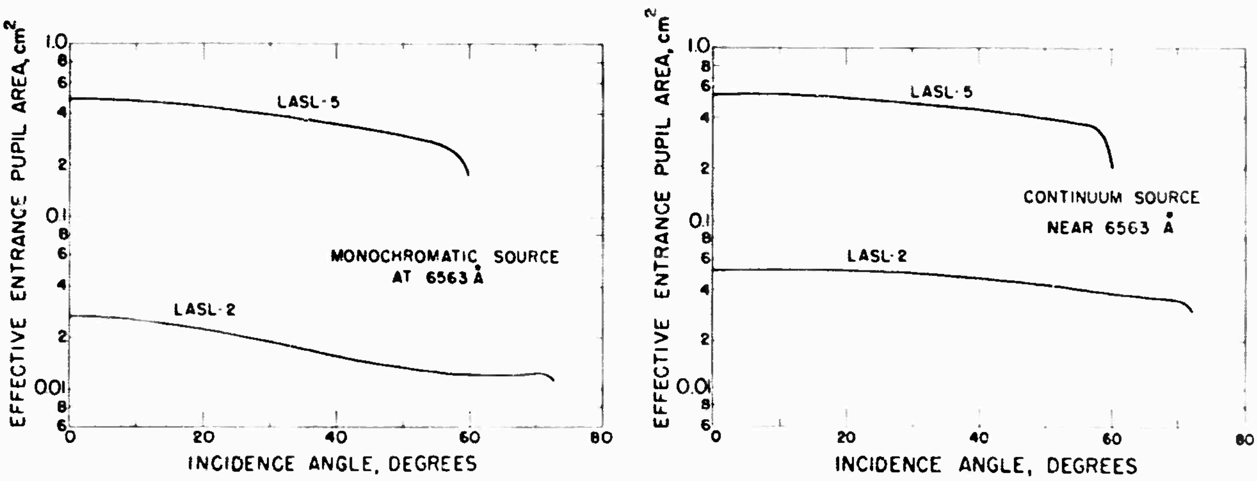
(a) Monochromatic Source (b) Continuum Source

Fig. 16. Effective entrance-pupil areas for 3914-Å photometers. Filters 20-Å half-width, 35% peak transmittance. For monochromatic source, entrance pupil of EG&G-5 with ND2 filter is larger at angles > 38° than same lens without filter due to the peak-wavelength shift with incidence angle and the fact that curves represent interference filters with different peak wavelengths.

A. Absolute Comparisons

Figures 16 and 17 are plots of the effective entrance-pupil areas as a function of incidence angle for the lenses. Source spectra are of two types: monochromatic at the design wavelength of the photometer, and uniformly continuous. The zero-degree incidence-angle intercepts are the effective on-axis entrance-pupil areas which would be measured with interference filters in place. They were calculated in the following manner.

The effective entrance pupil area, A_e, given for the filterless lenses in Table IV, represents an



(a) Monochromatic Source (b) Continuum Source

Fig. 17. Effective entrance-pupil areas for 6563 Å photometers. Filters 20-Å half-width, 65% peak transmittance. No curves for EG&G-5 are shown because interference filter for use at 3914 Å could not be removed.

infinitely broad filter of transmittance 1.0. If, instead, the filter transmittance is T_o, the effective area becomes $A' = T_oA_e$. If the filter passband now narrows to an effective spectral bandwidth of Λ_f, with maximum transmittance of T_o, and the spectral passband is broadened by the lens to width $\Lambda_e > \Lambda_f$, the effective entrance-pupil area at the passband peak is decreased to $A_m = T_oA_e\,\Lambda_f/\Lambda_e$. This is the intercept used in plotting the absolute monochromatic source response.

To a first approximation, the broadening of the filter passband by the lens has no effect on the wavelength integral of the passband.[11] The effective entrance-pupil area for a continuum source on the lens axis is therefore given by the filter-peak transmittance, T_o, i.e. $A_c = A_eT_o$; this value was used in plotting the continuum-source response.

The curves of Figs. 16 and 17 are related to the angular-response variables defined in Section II in the following ways. For the response to a monochromatic source at wavelength λ_o, [Figs. 16(a) and 17(a)], the curves are plots of $A_m\,R(\lambda_o,\theta)$ vs θ. For the response to a continuum source, [Figs. 16(b) and 17(b)], the curves are plots of $A_c\,R_{max}(\theta)\,\Lambda(\theta)$ vs θ. The curves can be consulted with reference to the calculations given in Section II, and in particular to the expressions in Table I, so that signal-to-noise ratio dependence on incidence angle can be estimated for various values of environmental parameters.

It is clear from the curves of Fig. 16(a) that for a monochromatic source at 3914 Å the largest effective entrance pupil area is exhibited by the EG&G-5, both with and without the ND2 filter. The maximum performance, however, occurs over a limited field of view, (a) for a region about the zenith for the lens without the ND2 filter, and (b) for a conical shell centered at 40° zenith angle when the ND2 filter is installed. The LASL-5 effective entrance pupil area is smaller by a factor of ~ 10 for on-axis light than that of the EG&G-5 without ND2 filter, and smaller by a factor of ~ 2 at 40° when the ND2 filter is used; but its angular response is much more uniform, decreasing by only a factor of ~ 2 at 60° from its maximum at 0°.

When a light source is isolated within the limited field of view of the EG&G-5, its response exceeds that of the LASL-5. However, the LASL-5 response can be the larger, for two cases: (a) an extended light source, as represented, for example, by the total scattered light from a lightning flash; or (b) for a light source which is concentrated outside the EG&G-5 field of view, such as an off-zenith air-fluorescence pulse or lightning intracloud discharge.

The effective entrance-pupil area of the LASL-5 for a monochromatic source is ~ 15 times larger than that of the LASL-2, both at 3914 Å (Fig. 16) and 6563 Å (Fig. 17). This breaks down into a factor of 10 due to the difference in geometrical area, and a factor of ~ 1.5 produced by the observed LASL-2 passband broadening.

B. Evaluation of Passband Characteristics

In Section II the desirable passband characteristics were listed, and possible causes of response ambiguities were discussed. These criteria will now be used to evaluate the results of the measurements.

1. LASL-2. The effective spectral bandwidth of the 3914-Å LASL-2 photometer, when equipped with a 20-Å filter, is 44 ± 5 Å over the whole field of view [Fig. 15(a)]. This is uniform enough to preclude significant ambiguity of response for this photometer near 4000 Å. The line response is not ideal, but it is usable. The shift in peak-response wavelength as a function of incidence angle is less than ± 3 Å from the mean [Fig. 14(a)] and creates no ambiguity.

At 5000 Å and higher, the spectral passband depends more strongly on incidence angle, and the passband curves become so broad that the performance of this lens for a monochromatic source is not desirable. If a continuous-spectrum source is to be detected, only if there are no significant changes in the spectrum over the limits of change in breadth of the spectral passband can there be insignificant response ambiguity.

The LASL-2 photometer therefore is usable, either for nuclear-explosion-excited-fluorescence detection or for lightning discrimination, without restriction near 4000 Å and, within the framework of the restrictions listed, for wavelengths ≥ 5000 Å.

2. LASL-5. The effective spectral bandwidth of the LASL-5 photometer equipped with a 20-Å filter is 25 Å throughout the visible, and is independent of incidence angle [Fig. 15(a)]. Theoretically, the optimum filter width is 15 Å, which would produce a 20-Å-spectral-bandwidth photometer. The peak-response wavelength shifts less than ± 3 Å from its mean as a function of incidence angle [Fig. 14(b)].

The LASL-5 photometer is therefore usable without restriction over the wavelength region 3900 to 6600 Å and, in fact, approaches the ideal line-source response for all wavelengths and incidence angles up to 60°.

As an example, consider an improved version of the LAAFDS, using LASL-5 photometers at 3914 Å for N_2^+ 1N (0,0) detection from air fluorescence, and at 6563 Å for Hα detection in lightning. Regardless of where within the 120° field of view the source occurs, the photometer responses bear a known, unambiguous relation to the source spectrum. If 3914-Å radiation is present, it is certain to occur at the peak-response wavelength of the 3914-Å photometer. The discrimination system thus can be set to give optimum performance, as determined from the lightning and air fluorescence spectra, and the minimum-obtainable false alarm rate will prevail.

3. EG&G-5. The response curves for the 3914-Å EG&G-5 lens with a 20-Å interference filter, with and without the ND2 filter, are rapidly changing functions of incidence angle, in contrast to those of the LASL-designed lenses. For this reason, the shift and broadening of the spectral passband curves are discussed only for incidence angles at which the response is greater than 10% of its peak.

a. Without ND2. The response falls below 10% of its zero-degree maximum at 35° incidence angle for a monochromatic source and at 53° for a continuum source [Fig. 13(e)]. The spectral bandwidth varies from 20 Å on-axis to 50 Å at 35° and 75 Å at 53° [Fig. 15(b)]. This represents a change of a factor of 2 within the monochromatic-source field of view, and a factor of 3 for a continuum source. The peak-response shift relative to 0° is 24 Å at 35° and 44 Å at 53° [Fig. 14(c)]. These data indicate an ambiguity of response to a line-spectrum source. Response to a continuum source is acceptable if the continuum is uniform over the whole wavelength region covering the shift and broadening of the spectral passband.

For example, consider the responses of a discrimination system using EG&G-5 photometers, without ND2 filters, to an air fluorescence pulse. If the pulse occurs at the zenith, the photometer responses will match the spectrum, since the passbands at zero degrees are narrow and are accurately peaked at the design wavelengths. The discrimination-channel response will be small, relative to 3914 Å, and the pulse source will be recognizable as air fluorescence.

However, if the source occurs at some incidence angle other than the zenith, the shift and broadening of the spectral passbands will cause a decrease in the 3914-Å response which is greater than the corresponding decrease in the (continuum) discrimination-channel response. The discrimination-channel response may in this case be a large enough fraction of the decreased 3914-Å response so that the ratio approaches that typically produced by lightning. If the discrimination ratio is set to reject all detectable lightning pulses, which is possible by using a high enough discrimination ratio, the off-zenith air-fluorescence pulse will also be rejected, a clearly unacceptable result. The discrimination ratio must therefore be set at a lower value, so that all air-fluorescence pulses will be accepted. When this adjustment is made, some lightning pulses will also be accepted; and thus it will no longer be possible to determine the source of a pulse unambiguously from the signals. Furthermore, the accepted lightning pulses will produce a higher than optimum false-alarm rate.

b. With ND2. Incidence-angle limitations (response ≥ 10% of maximum) for the EG&G-5 lens with the ND2 filter are approximately 50° to 60° for both line and continuum sources [Fig. 13(f)]. In this range the spectral bandwidth varies from 33 to 60 Å [Fig. 15(b)] and the peak-response-wavelength shifts over 40 Å [Fig. 14(c)]. Again, the line-source response is ambiguous, since the same argument presented for the lens without filter applies in this case, with "zenith" replaced by "40° incidence angle." The limitation to continuum-source response acceptability also applies.

C. Recommendations

1. Original System. The LASL-2 photometers designed for the LAAFDS have been shown to be adequate without reservation for wavelengths near 4000 Å, although they are limited in detection sensitivity compared to the later designs. Under the present concept of the lightning-discriminating LAAFDS, the channels at 3914 and 4150 Å produce equivalent sensitivity and good spectrum recognition. Some improvement in spectrum recognition and lightning-discriminating capability can be realized by changing the discrimination channel either to 4120 Å, retaining the 20- to 30-Å filter, or to 4860 Å with a 130-Å filter. The latter channel would give nearly a factor of 2 improvement in signal-to-noise ratio in the discrimination channel, on the basis of the typical lightning spectrum.[6] Monochromatic features of the lightning spectrum at 5000 or 6563 Å, recently suggested as useful discriminants when using 20-Å-spectral-bandwidth photometers, would not be suitable for a discrimination channel in a system using LASL-2 photometers.

2. Advanced Systems. Advanced designs of the LAAFDS, or similar systems, are intended to be used with more sensitive detection and/or discrimination detectors than those in the original LAAFDS design. Of the two larger lens designs evaluated here, the LASL-5 has been shown to be the more uniform and predictable in response, and the more flexible in application.

While the EG&G-5 is the more sensitive for some incidence angles, the shift and broadening of the spectral passband combine to negate this advantage. Lightning discrimination on the basis of spectral differences requires unambiguous response by the detectors. The 3914-Å EG&G-5 photometer has been shown to be subject to ambiguity of response for certain values of incidence angle. Use of the EG&G-5 in a lightning-discrimination system would yield less than optimum performance, and an unnecessarily high false-alarm rate.

The opposite is true for the LASL-5 lens. Its spectral passband is only slightly broadened for filter bandwidths as narrow as 15 Å, and the bandwidth is uniform at all incidence angles $\leq 60°$. The $\pm$ 3-Å peak-wavelength shift is negligible. Spectrum recognition is ideal for either narrow 20-Å bandwidths or the broader bandwidths desirable for continuum-response discrimination channels.

It is therefore concluded that the LASL-5 lens is the more suitable for advanced detection and discrimination systems.

ACKNOWLEDGMENTS

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